A Silicon Photonics Platform with Heterogeneous III-V Integration

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Abstract: We present a silicon photonics technology platform combining silicon processing technologies and heterogeneously integrated III-V materials. This enables passive and active photonic functions on silicon, such as waveguide circuits, filters, modulators, photodetectors and integrated lasers.

OCIS codes: (130.3120) Integrated optics devices; (130.3130) Integrated optics materials

1. Introduction

Silicon photonics has become a well-accepted technology with a considerable potential for large-scale industrial adoption [1]. This can be attributed to two important factors: the material properties of silicon make it extremely useful for dense integration of passive photonic circuits for wavelengths beyond 1.2um, and this can be done using the established industrial tools and processes used for the manufacturing of CMOS electronics. This combination has driven the field of silicon photonics forward at an amazing pace, despite some of its prominent drawbacks. Silicon has a relatively weak interaction with light, so making efficient electrooptic modulators is not straightforward, as silicon has no intrinsic electro-optics effects, and thus modulators have to rely on carrier-dispersion effects, which are inherently limited in speed and introduce unwanted absorption. Also, integrating photodetectors requires incorporation of Germanium or other materials. While this material is already available in CMOS foundries, it can introduce complications.

However, the most difficult component to integrate with silicon photonics is the light source. Because of its indirect bandgap, silicon is a notoriously bad light emitter, and even Germanium needs aggressive manipulation to coerce it into efficient emission of light. The most efficient semiconductor lasers are made of III-V materials, and therefore we are exploring the heterogeneous integration of thin films of III-V materials on silicon photonics circuits, which we can then further process into integrated lasers, but also detectors, amplifiers and even efficient modulators.

In this paper, we will discuss the progress of imec's silicon photonics platform (iSiPP) technology and recent results of the Photonics Research Group in heterogeneously integrating III-V components with silicon photonics.

2. Passive Waveguide Circuits

Silicon is a good material for passive waveguides: it has a high refractive index contrast with the surrounding oxide, which allows downscaling to submicron cross sections and 3 micrometer bend radii. However, the high contrast in these photonic wires also induces propagation losses, mainly due to scattering at sidewall roughness. Propagation loss is therefore an important metric for waveguide quality. In the past years, reported waveguide losses have dropped to a few dB/cm, with the best results just below 1dB/cm for e-beam fabricated wire waveguides. The waveguide we fabricate in imec with 193nm deep UV lithography have losses of 2.7dB/cm with an air cladding, and 1.7dB/cm with an oxide top cladding (the lower index between silicon and oxide reduces the scattering losses). Broadening the waveguides, or replacing the high-contrast wire waveguide with a lower-contrast rib waveguide, can lower the losses down to 0.24dB/cm [7]. In fact, transitioning from a wire to a rib waveguide can be used for low-loss crossings, MMI splitters and at interfaces with a slab waveguide [8].

Apart from just routing light on a chip, passive waveguides are used a lot as wavelength-selective filters [8]. The high group index and the sharp bends of the silicon wires allow very short delay lines, with a large free spectral range. We have demonstrated ring resonators and interferometers, but also more complex wavelength selective components such as AWGs and echelle gratings, with very good performance: insertion loss in the order of 1-3dB, and crosstalk levels of 20-25dB. This good performance can be attributed to process quality: in interferometric filters, non-intentional crosstalk is largely determined by phase noise. E.g. in an arrayed waveguide grating the phase noise could be induced by unequal optical delays between the arms. Also small nonuniformities in waveguide width would induce variations in effective index, and thus in optical length. The process quality can also be assessed by checking the matching of devices: comparing the spectral response of identically designed devices on a chip, or between different chips, wafers and even batches. With good process control, we have shown that it is possible to use CMOS fabrication tools and processes to get wavelength control within 1nm, which amounts to a linewidth control (averaged over the delay line) of 1nm [9].

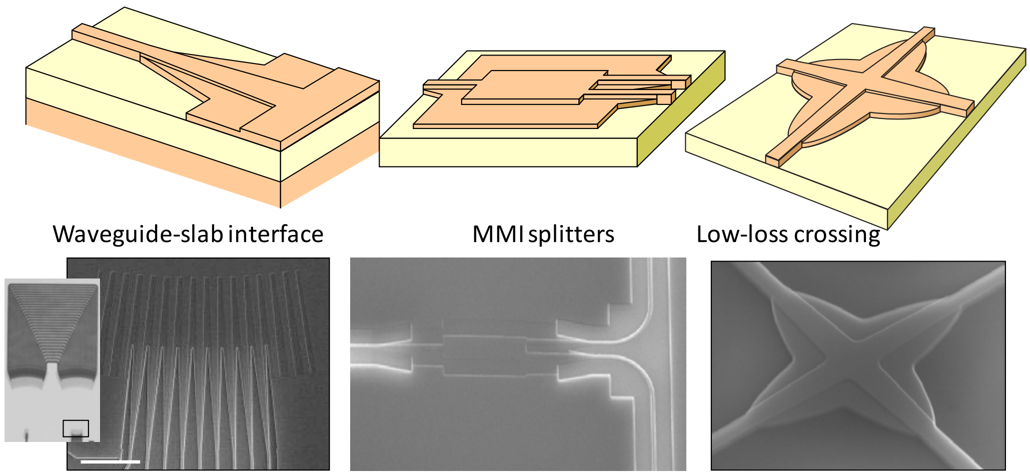

Figure 1: Passive waveguide components with a two-step etch profile.

3. Active silicon devices

Apart from passive silicon circuits, silicon can also be used to electrically manipulate light on a chip. This can be done through temperature or by manipulating the carrier density in the waveguides. For the first approach one can incorporate heaters in or close to the waveguide circuits. For manipulating the carrier density in the waveguide, one can implement a diode or a capacitor. Imec has integrated such carrier dispersion modulators in its platform process and demonstrated modulation efficiencies similar to those reported in literature, with $V_\pi.L_\pi$ values well below 1.5Vcm.

4. Integrating III-V materials

Because silicon cannot accomplish all optical functions, especially the generation of light, we have developed a technology to integrate III-V materials on a silicon photonic circuit. While epitaxy would be considered to be ideal in a semiconductor environment, III-V epitaxy on silicon is far from straightforward, especially when laser-quality substrates with multiple quantum wells or quantum dot layers are required. Hybrid integration, whereby prefabricated components are integrated with the waveguides using accurate pick-and-place equipment does allow for prescreening of the lasers, but is not compatible with wafer scale integration, Therefore, our approach relies on bonding, and more specifically, adhesive bonding. III-V dies are glued to the silicon substrate with a thin layer of BCB. Subsequently, the dies are thinned down by grinding polishing and wet etching to a thin film of III-V material, which can then be processed with planar technologies, just as the silicon circuit [6]. Depending on the application, the BCB thickness varies from 300nm down to 30nm, and the III-V layer stack can be as thick as several micrometer, and as thin as 100nm. The III-V material is then processed into lasers [1][4], amplifiers, photodetectors [3], etc.

5. On-chip laser sources

For compact laser sources, we decided to focus on microdisk type devices. There, the laser mode is a whispering-gallery mode on the outer rim of a InP microdisk (6-10um in diameter), evanescently coupled to the silicon waveguide buried underneath. Initial devices were optically pumped [26], [27] or not yet coupled to silicon waveguides [28]. In 2007, we demonstrated for the first time an electrically injected microlaser [29]. These first devices suffered from significant thermal rollover due to self-heating (the adhesive bonding and subsequent metallizations wrapped the microdisk laser in thermally insulating BCB). Subsequent iterations improved the III-V layer stack as well as the thermal management through the incorporation of heat sinks and heat spreaders in the electrical contacts. This resulted in microdisk lasers with a waveguide-coupled output power up to 120uW, for a driving current of 4mA.

Its compactness makes the microdisk laser exceptionally suited for integration of many devices on chip. Also, by varying the radius, lasers at different wavelengths can be designed, even on the same bus waveguide, effectively creating a multi-wavelength laser. In addition, the III-V material could be used to incorporate a heater next to the laser, allowing for thermal tuning [5].

For higher output powers, larger laser structures are required to provide sufficient gain without excessive effects of self-heating. An optimal laser cavity design should consist of a section where the optical mode is completely confined to the III-V waveguide layer, with efficient coupling to the silicon waveguide. Ideally, the wavelength selective feedback can be provided by structures defined in the silicon, as the patterning in silicon can be better controlled, and can also provide the best alignment and coupling to the silicon waveguides.

The straightforward approach to accomplish this is to use an adiabatic tapered coupling to transform the optical mode from a III-V confined mode to a silicon confined mode. Such a integrated laser, with a coupling section of 150um, has recently been demonstrated [1].

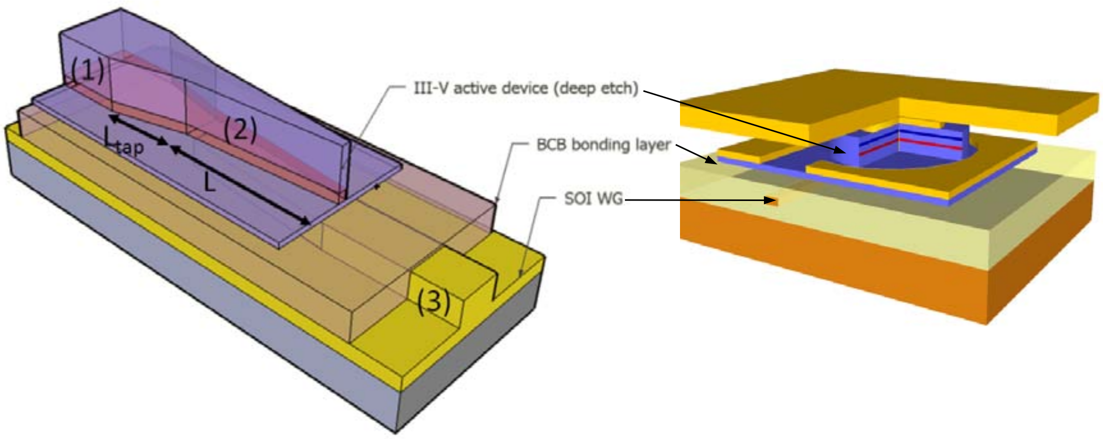

Figure 2: Heterogeneously integrated lasers. Left: transition section of a stripe laser. Right: Microdisk laser.

6. Conclusion

We have developed a technology platform for silicon photonics which enables not only passive and active silicon circuits, but also enables heterogeneous III-V integration through BCB adhesive bonding. In this technology we have demonstrated a wealth of passive waveguide devices. The III-V material can be used for photodetectors, but its main utility lies in on-chip laser sources. We have shown different types of laser sources, from compact microdisk lasers to mW-level stripe lasers coupled to a silicon waveguide.

Acknowledgements

Part of this work was supported by the European Union in the framework of the projects ICT-HELIOS and ICT-WaDiMOS. Wim Bogaerts acknowledges the Flemish Research Foundation (FWO-Vlaanderen) for a postdoctoral fellowship.

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